# Cassini Orbit Determination Performance (July 2008 - December 2011)

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**This paper reports on the orbit determination performance for the Cassini spacecraft from July 2008 to December 2011. During this period, Cassini made 85 revolutions around Saturn and had 52 close satellite encounters. 35 of those were with the massive Titan, 13 with the small, yet interesting, Enceladus as well as 2 with Rhea and 2 with Dione. The period also includes 4 double encounters, where engineers had to plan the trajectory for two close satellite encounters within days of each other at once. Navigation performance is characterized by ephemeris errors relative to in-flight predictions. Most Titan encounters 3-dimensional results are within a 1.5 formal sigma, with a few exceptions, mostly attributable to larger maneuver execution errors. Results for almost all other satellite encounter reconstructions are less than 3 sigma from their predictions. The errors are attributable to satellite ephemerides errors and in some cases to maneuver execution errors.**

## I. Introduction

The Cassini spacecraft has now completed both its prime mission (in September 2008) and first extended mission (in September 2010). It is now in its second extension, doing its 167th Saturn revolution at the time of this meeting.

After the completion of 4-year prime tour in July 2008, NASA extended the mission at full capacity (engineering and scientific intensity, manpower and budget) until September 2010, after which NASA extended the tour one more time until 2017 at almost the same pace[a]. The first extension, from July 2008 to September 2010 was judiciously named the Cassini Equinox Mission, as this segment of Cassini's journey was primarily focused on changes wrought on Saturn by the onset of equinox, when the sun shone directly on the gas giant's equator on August 11, 2009, a phenomenon that happens just once every 15 years. The second extension, which goes through September 2017, is named for the Saturnian summer solstice occurring in May 2017. Since Cassini arrived at Saturn just after the planet's northern winter solstice, the extension will allow for the first study of a complete seasonal period.

This paper reports on the navigation performance from an orbit determination point of view from the beginning of the Equinox tour from July 2008 to the end of the first year of the Solstice tour in December 2011. During this period, Cassini made 85 revolutions around Saturn, had 52 close encounters: 35 of Titan, 13 of Enceladus, 2 of Rhea and 2 of Dione. This includes 4 double encounters, where navigators had to plan for the trajectory for two close satellite encounters within days of each other at once. A summary of all encounters within this period is shown in Table 2. The table shows the targeted epoch and altitude for each encounter along with the achieved deltas. Note that the encounters are referred to by the first letter of the target (T for Titan, E for Enceladus, etc) and the number associated with the encounter in the mission (First Enceladus is E1, second E2, etc).

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[a]Budget reduced at 75% of prime mission for science and 60% for engineering

As reported by Antreasian et al.,[1,2,3] the orbit determination performance during the four years of the prime tour enabled vast improvements in the determination of Saturn and Saturnian satellite ephemerides and masses, Saturn gravity and pole, as well as the non-gravitational forces affecting the spacecraft's motion. These improvements in the orbit determination processes along with Cassini's accurate maneuver performance and the use of spacecraft telemetry have helped eliminate several planned statistical maneuvers which were scheduled to clean-up orbit determination or maneuver-execution errors during this phase of the tour.

The data used for OD consist of radio metric Doppler and Range from NASA's Deep Space Network (DSN), augmented by Optical images of Saturn's satellites (OpNav) against a background of known stars. At the beginning of the mission, OpNavs were critical in determining the orbital motion of the satellites. While not critical anymore, OpNavs are still processed from time to time to maintain knowledge of the satellite ephemerides.[4]

With uncertainty less than 300 m, Titan's orbit error is not a major contributor to the orbit determination anymore, though kilometer-level errors can be costly as its impressive gravity greatly influences the trajectory. At the beginning of the Equinox tour, the uncertainty in Enceladus, Rhea and Dione ephemerides were about 2 km, 3 km and 4 km, respectively. Despite large improvements from the earlier Enceladus-4, 5 and 6, (E4, E5 and E6) encounters, Enceladus' uncertainty grew back to 2 km a year later for E7. As such, about 22 pictures were processed between the E6 and E7 encounters. For Rhea and Dione, about 34 and 46 pictures were processed up to the R3 and D2 encounters.

## II. Orbit Determination Overview

To support the navigation up to a targeted encounter, the orbit determination (OD) process divides the trajectory in data arcs that begin near Saturn apoapsis one and a half orbital revolutions prior to the encounter. The data arc generally cannot extend beyond two satellite encounters because of limitation to the OD process.[1] Cassini's orbit determination is dependent on 2-way X-Band Doppler and range tracking data acquired via the DSN, as well as OpNav. Generally, six-hours of radio-metric data is acquired per day. The OpNav schedule during the Equinox tour phase consists of images shuttered at a rate of 1 image every 4 days, and has been greatly reduced for the Solstice tour. As satellite ephemeris errors were the major navigation error source prior to the Cassini encounters, this reduction is possible since the ephemerides are now well determined. The use of OpNav now only helps to prevent growth in the satellite ephemeris uncertainties.[4]

Depending on the number of propulsive events in the arc, about 110 to 170 parameters are estimated in the OD process. This also includes spacecraft, satellites[b] and planet state parameters, gravity and pole orientation coefficients, measurement biases as well as non-gravitational accelerations. For each data arc, the spacecraft initial state at the arc's epoch was estimated as Cartesian position and velocity in a Saturn-centered Earth-Mean-Equator and Equinox of 2000 (EME2000) frame. The a priori values were taken from a previous data arc OD solution along with the state covariance matrix mapped to the new epoch. The estimated satellite and planet parameters from the prior arc solution were used to establish an updated model. The post-fit correlated covariance of these parameters was then used for the new arc's a priori covariance. At 9.5 A.U., thermal radiation pressure from Cassini's onboard power supply is one magnitude greater than solar pressure. This force was modeled as an exponential acceleration. A scale factor was estimated in each of the spacecraft axes with an a priori uncertainty equal to 10% of the nominal values. The force due to solar pressure was included in the spacecraft orbit integration with nominal reflectivity values, but no parameters were estimated. During each data arc, three to four maneuvers are generally scheduled using either the spacecraft main engine for large burns ($> 0.3$ m/s) or the Reaction Control System (RCS) thrusters for smaller burns ($< 0.3$ m/s). For each maneuver, the magnitude, direction and start time of the maneuver were estimated using an a priori uncertainty based on the execution-error model which accounts for fixed and proportional errors. Once the maneuver has been performed, the pointing is further constrained from the telemetry data. More details on this subjects discussed by Roth et. al.[5] The reconstructions of these maneuvers based on the orbit determination included in this paper are reported in three papers from Cassini Navigation.[6,7,8]

RCS thrusting due to the Reaction Wheel Assembly (RWA) biasing, spin downs, attitude turns, attitude control on the RCS system (deadbanding) were modeled as impulsive maneuvers. As discussed by Ardalan et. al,[9] spacecraft telemetry is also often used to update and constrain the magnitude and/or pointing of RCS propulsive events. It should also be noted that drag acceleration parameters were estimated for low altitude

[b] The nine major satellites of Saturn: Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus and Phoebe

Titan encounters (<1200 km) where the spacecraft briefly enters the upper layers of Titan's atmosphere. During this time, the spacecraft attitude is controlled by the RCS system and properly modeling all the forces has been proven beneficial for accurate navigation and satellite estimation, as discussed in Pelletier et al.[10,11]

Errors in Earth rotational parameters as well as DSN station location are also considered in the filter. Finally, stochastic acceleration parameters are used to take into account any mis-modeling and ensure any error isn't propagated forward through the other bias parameters that are being estimated. In the beginning, the stochastic parameters were used to take into account the mis-modeling of the solar radiation pressure, though they are also used now to taking into account the error in the RCS thrust. More details on the orbit determination process have been presented in a Space Ops paper by Antreasian et al.[12]

## III. Encounter Results

Including post-encounter radio-metric data in the OD filter allows for reconstructions of the target coordinates. Figures 1, 2 and 3 show the reconstructed encounter-relative positions in the Bplane[c] compared to predictions fromthe Navigation's last control points. The associated 1-$\sigma$ uncertainty ellipses of the solutions are also shown. A statistical analysis for all encounters is provided in Table 3, where the 3-dimensional errors (2D Bplane combined with down track error) are reported both in kilometers and standard deviations ($\sigma$). The Delivery Accuracy Probability column show the probabilities associated with the 3D predictions. One may interpret this as "How often can we expect to do better?" Thus a small percentage means the prediction was good while large percentage means it was not.

Titan encounters are usually well predicted. Mainly because after more than 50 encounters, the orbital parameters that define the motion of Titan are well known. Most Titan encounters 3D results are within 1.5 formal $\sigma$, with a few exceptions, mostly attributable to larger maneuver execution errors. While not catastrophic for either science or navigation, some of these cases caused downstream propellant cost. The most significant example is the Titan-46 encounter, where the approach maneuver, OTM169, had a large execution error that caused a near 10-km miss at Titan. This led to a propellant penalty of approximately 6 m/s in order to properly retarget the spacecraft to the reference trajectory. This poor maneuver performance eventually led to a swap to the redundant RCS thruster branch. The performance of the maneuvers during this period is discussed in more details by Gist et. al.[6]

It can also be noted that the prediction errors are affected by Reaction Wheel biases that are placed between the approach maneuver and the encounter. Error in the delta-V predictions for such biases causes trajectory deviations that lead to encounter errors. For this reason, careful planning during the mission sequence development tries to avoid placing biases at such locations, though it is not always possible.

The OD performance for the encounters with the icy satellites (Enceladus, Dione, Rhea) were mostly within 3 $\sigma$. The magnitudes of the miss are quite small and the impact on navigation and propellant is almost nil since the bodies are far less massive than Titan. The errors are attributable to corrections to the satellite ephemerides. For Enceladus, the frequent encounters are paying off and we see less errors than during the prime mission, thanks to a better knowledge of its orbital motion. In the 1 year that separated E6 and E7, Enceladus made more than 260 revolutions around Saturn. Ephemeris prediction knowledge quickly deteriorate at that rate, being in direct correlation with the planetary system's GM uncertainty. Though following E7, E8 had a similar error of 1.7$\sigma$. In this case, it was discovered that the E7 gravity gradient did not provide good geometry to solve for the out-of-plane component of the spacecraft state at epoch, for which its covariance was scaled by a factor of 5. This is done primarily to avoid carrying systematic errors over from one OD arc to the next. However, learning from the E7/E8 errors, the recommendation came out to keep the formal state uncertainty unscaled when the first encounter in the OD arc is gravitationally too weak. An analysis of all the encounters in the mission has helped identified these cases.

The Rhea-2 and Dione-2 encounters were 3.6 and 7-kilometers off, respectively. This yielded $\sim 3\sigma$ errors for both, which is attributable to ephemeris errors. Note that the orbital periods of Dione and Rhea are approximatively 2.7 days and 4.5 days, respectively. As a result of Rhea-2, the Rhea-3 encounter was less than 1-km off its predicted position.

As mentioned before, this period of the Cassini tour saw 4 double-encounters. The events are listed in Table 2: E6/T46 in October 2008, T67/D2 in April 2012, E10/T68 in May 2010 and D3/T79 in December

[c]The Bplane is defined as the bplane perpendicular to the incoming asymptote to a target body. See Referece[13] for details.

2011. Cassini defines a double encounter when the spacecraft has two close satellite approaches within days of each other, where it is not possible to control the trajectory in between. Thus, only one of the encounter is specifically targeted with the approach maneuver and the navigation team has to make sure that the requirements are met for both encounters at that time. Table 1 summarizes the statistical results for each double encounters. E6 and T46 followed the poorly performed OTM-169 maneuver, as mentioned before, which affected both encounters. For T67 and D2, a large correction in Dione's ephemeris took place, though the miss could have been a lot worse if not for the the good results at Titan-67. Note that the decision to target D2 rather than T67 explains the large differences seen in the T67 results in Table 2. E8 and T68 were reasonably well predicted with only a $2\sigma$ miss for E8 that did not really influence T68. For D3 and T79, however, a $3\sigma$ miss at D3 from ephemeris errors caused a trajectory deviation in the order of 10 km at T79.

# IV. Parameter Estimation Results

As discussed, the Cassini OD process requires an estimate of a great variety of spacecraft, planet, satellite and measurement parameters. In order to properly assess the performance of the complete orbit determination, it is important to take a global view of the parameters over the entire length of the tour. Most parameters share commonality between OD arcs, such as gravitational constants, and the estimated values should show consistency as well as a gradual improvement in uncertainty. It is important, however, to note that this consistency does not have to be perfect in order to ensure successful navigation. Occasionally, the formal uncertainties are too tight and need to be loosened using engineering judgment based on both analysis and past experience.

## A. Measurements and Stochastic Parameters

Figure 4 presents the measurement residuals for all the Doppler, range and OpNav data that went into the OD for all the arcs in the 2+ year period being studied. It can be seen in the Doppler data that the noise greatly increases with periods when the spacecraft is in solar conjunction. This occurs once a year when Saturn and Earth are aligned on opposite sides of the Sun such that the radio waves have to travel through solar plasma. The Doppler data becomes noisy and the range data is biased. Navigation will typically de-weight the Doppler and delete the biased range data when this occurs, to not get a false trajectory estimation. For this reason, maneuvers and encounters are not scheduled during solar conjunction.

Overall, the goal in OD is to take out any signature in the data so that all that is left is the noise with a zero mean. Stochastic acceleration parameters are used to take out any unusual signatures in the data, though anything beyond a threshold of $5\times10^{-13} km/s^2$ is carefully analyzed[d]. The stochastic acceleration estimates are shown in Figure 6. With a zero mean, the standard deviation of the data set is clearly well below $5 \times 10^{-13} km/s^2$. The outliers that reach $1.5\times10^{-12} km/s^2$ correspond to either the uncertainty associated with periods where the spacecraft was in RCS control or at Saturn periapsis. The RCS control thrust is modeled in the OD, but not estimated, so it is expected to see larger stochastic acceleration estimates. In fact, the frequency and uncertainties of the stochastic accelerations are typically increased during those periods. The Saturn ephemeris parameters are estimated, but the formal uncertainty is so small now that it probably has reached its limit in the OD process. While this issue does not affect the navigation performance (this is why the stochastic parameters are beneficial: the errors are not propagated through Saturn ephemeris corrections), the OD team is currently re-evaluating the strategy with the estimation and propagation of Saturn.

## B. Small Forces

As with any other spacecraft with reaction wheels, angular momentum management is periodically performed on Cassini. Cassini uses the RCS thrusters to perform this, and because the thrusters are not balanced in one of the spacecraft axes,[9] small propulsive events, or small forces, on the order of millimeters per second are imparted to the spacecraft. The small forces need to be modeled to properly propagate the spacecraft trajectory and filter the radio data. The events are typically performed when the DSN is tracking Cassini, so that the maneuvers can be clearly seen along the Earth-line Doppler data. Prediction for the small forces comes from a spacecraft flight simulator and Navigation uses impulsive maneuvers to model them.

[d] This value corresponds to the uncertainty in the solar radiation pressure model[1]

An uncertainty of 1.2 mm/s is assigned to each event. As this is not always possible, navigation also relies on spacecraft telemetry to firm up the estimate of the small forces. The differences between the prediction and the OD estimates for the small forces are shown in millimeter per second in Figure 5(b), with the corresponding $1\sigma$ uncertainties. Rarely does the error grow to more than 1 mm/s.

### C. Thermal Radiation

The thermal radiation pressure from Cassini's onboard power source is modeled with an exponential acceleration. Figure 5(a) shows the estimated accelerations in each axis since the beginning of the tour, along with $1\sigma$ uncertainties. Note that the values have been normalized to the pre-tour mass in order to be able to compare them together. While the data shows some inconsistencies and/or trend, the numbers are small and well within $3\sigma$.

### D. Saturnian System Gravitational Parameters

The estimation of gravitational constants for Saturn and its major satellites is inherent to the Cassini orbit determination process. The gravity and orbital motions of all the bodies in the Saturnian system affect the trajectory of Cassini, especially around close encounters. Along with the planetary GM, the GM for the nine major satellites of Saturn are routinely estimated in each OD arc. The planet GM itself is inferred from the relationship between the barycenter and the moons. At this moment in the mission, no ring mass is considered, and studies have shown that OD is not sensitive to that. This may however change towards the end of the Cassini mission, when the spacecraft is scheduled to fly between the innermost ring and the planet. More details on the proposed end-of-mission scenario can be found in Buffington et. al.[14] For Saturn, besides the barycenter GM, OD is estimating the first two zonal harmonic coefficients, J2 and J4, as well as the right ascension and declination of Saturn's pole, which is coupled to the harmonic coefficients. These results are shown in Figure 7, along with $1\sigma$ uncertainties. It is important to note that the parameter estimates are tied to a global satellite and planet model covariance, which contains correlated information of all of the gravitational parameters as well as the ephemerides parameters. For instance, the covariance reflects correlations from the resonance between some of the moons: Mimas with Tethys, Enceladus with Dione, and Titan with Hyperion and Rhea. This covariance was formed from the radiometric and optical navigation images taken by Cassini, as well as the historical information gathered from Earth-based astrometric observations and the Voyager and Pioneer spacecraft. While a localized Saturn and satellite ephemeris and gravity are routinely estimated and the covariance updated in the daily OD operations, a global determination is performed periodically using all the observations to date and fed back into the daily operations. The results in Figure 7 show that while variations are observed in most parameters, they are within $3\sigma$ and thus statistically consistent. The changes observed in the parameters typically correspond with close encounters and/or new global OD fits.

In addition, further OD studies from gravity encounters have enabled the determination of gravity field coefficients for some of the satellites, namely Titan, Rhea and Enceladus. This is possible when the spacecraft is tracked by the DSN during the closest approach. Results from these studies are fed back to the models used by the navigation team. This has helped increase the accuracy of the moon's GMs and thus the navigation performance post encounters. One good reference for this is the paper by Jacobson et. al.[15] On example is with the Enceladus-9 encounter, where a significant reduction in Enceladus' GM uncertainty was observed (Figure 7(b)).

### E. Saturnian System Orbital Parameters

Figure 8 shows the trajectory differences for the barycenter and the satellites at various stages of the mission. The reference trajectory used in the comparisons correspond to the reconstructed trajectory obtained at the end of the study period, in December 2011. The plots show the evolution of the ephemerides from June 2008 and January 2010. The range of the plots is for the year 2011. All the comparison curves are a measure of how well the OD at that time was able to predict the satellites positions for 2011.

As expected, the transverse direction shows a secular drift, since this is tied to the time variability in orbits. The radial and normal differences are a measure of the differences in the size and orientation of the orbits. Most transverse drifts between the prediction in January 2010 (blue) and the reconstruction in December 2011 (the reference) are within a few kilometers at most, and even the old predictions from 2008 are within 15 kilometers. Between 2008 and 2011, Cassini made many revolutions around Saturn and by having OpNavs as well as frequent close encounters with the satellites, this ensured that the error growth was kept at a minimum. The navigation errors leading to a close encounter were never greater than 5 kilometer $1\sigma$ at any given time.

The uncertainties in the satellite parameters for each data arc since June 2008 are collected in Figure 9. It should be noted that the plots (and those in Figure 7) reflects a variation in strategy in the scaling of the satellite covariance. As discussed by Antreasian et. al.,[3] OD has been scaling the formal satellite covariance by a factor of three to take into account the rapid error building up from some of the satellite's transverse drift. This scale factor was taken out during a brief period in the extended mission between T61 and R2. It was believed at that time that the formal uncertainty from the global OD was adequate and that the problems observed during the E3 encounter were no longer an issue. Although this decision did not affect the navigation performance as no significant errors were observed (See Table 3 between T61 and R2), it was decided to revert back to a scale factor of 3 as it allowed more freedom in the filter and it removed the concern that the covariance could be over constrained.

In the case of Titan, it can be seen in the plots that the uncertainties never go above 200 m, thanks to the many encounters Cassini had with the moon. Enceladus shows a maximum uncertainty in the transverse direction of about 4 km before the scaling down period at T61. The series of Enceladus encounters in the following months further reduced the uncertainty, which has been maintained below 1 km since. Note, however, the rapid growth in the transverse direction. This is certainly due to the rapid orbital period of Enceladus tied to its very low uncertainty level.

Apart from an approach of approximately 10,000 km after T66, Mimas never really had a close encounter with Cassini, so its uncertainty is near 10 km. Dione's uncertainty was about 5 or 6 km prior to D2 in April 2010. A noticeable improvement in the transverse direction can be seen at that point, where it dropped below a kilometer. The effect of the resonance between Enceladus and Dione can be seen in the plot as well, where the uncertainty drops with the Enceladus encounter. The story is similar for Rhea, where the uncertainty dropped at R2 from 5-6 km to less than 1 km. The resonance of Rhea's orbit with Titan also helps to maintain its knowledge with each encounter.

The reconstructed $1\sigma$ spacecraft uncertainties are reported in Figure 9(j). At most, the uncertainty grows near 10 km at apoapses and is below 100 meters at periapses. Although this isn't shown in the plots, it should also be noted that the encounter-relative uncertainties are small, in the order of tens of meters for Titan and hundreds of meters for other satellites.

## Conclusion

The Cassini spacecraft continued to return extraordinary science results in the first extended mission as well as in the beginning of the second extension period which this paper covers. Thanks to a solid navigation performance, the project was able to meet all scientific requirements and to keep the spacecraft on course for the continuation of the mission. The orbit determination performance kept improving during the mission thanks to continuous improvement in the knowledge of the saturnian system ephemerides and gravitational parameters, to the use of telemetry to better characterize the performance of the propulsive events and by keeping the use of stochastic parameters in the OD process to a minimum. At this point the mission is well on its way to meet the goal of reaching the Saturn solstice in 2017.

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# Appendix
# Supporting Tables and Figures

**Table 1. Navigation Performance Summary: Double Encounters**

| Target | Last Control Point | 3D Position Error (km) | ($\sigma$) | Delivery Accuracy Probability (%) | Notes |
|---|---|---|---|---|---|
| Enceladus-6 † | OTM-169 | 4.2 | 3.6 | 99 | 1.8 $\sigma$ pre-encounter RWA bias error and |
| Titan-46 | | 9.7 | 4.0 | 99 | 5.4 $\sigma$ OTM-169 error |
| Titan-67† | OTM-241 | 0.9 | 1.4 | 40 | |
| Dione-2 | | 7.0 | 3.4 | 99 | 6 km Dione ephemeris error |
| Enceladus-8 † | OTM-247 OD | 1.4 | 2.0 | 75 | |
| Titan-68 | | 2.1 | 0.8 | 10 | |
| Dione-3 † | OTM-301 | 2.8 | 3.0 | 97 | Dione ephemeris error, which magnified |
| Titan-79 | | 10.8 | 4.2 | 99 | the miss at Titan |

† Not specifically targeted.

**Table 2. Targeted Encounters**

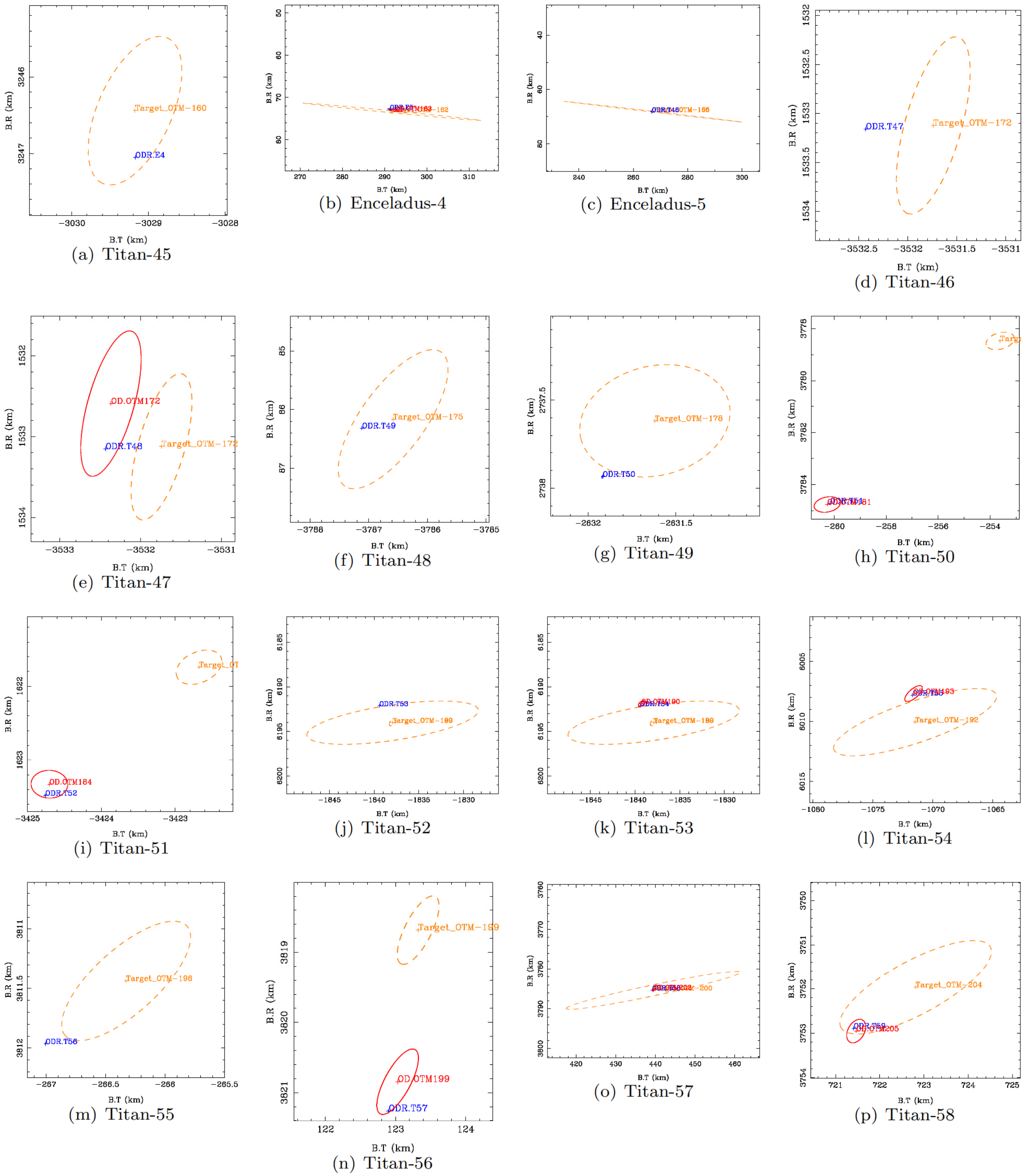
| Target | Reference | | Reconstruction (in Δs from Reference)† | |
|---|---|---|---|---|
| | Time of closest approach (TCA) | Altitude (km) | TCA (sec) | Altitude (km) |
| Titan-45 | 31-JUL-2008 02:14:16 | 1613.4 | 0.0275 | -0.4310 |
| Enceladus-4 | 11-AUG-2008 21:07:24 | 53.5 | -0.1107 | 0.6100 |
| Enceladus-5 | 09-OCT-2008 19:07:45 | 28.5 | 0.0356 | 0.4020 |
| Enceladus-6‡ | 31-OCT-2008 17:15:56 | 200.3 | 0.9292 | 27.7980 |
| Titan-46 | 03-NOV-2008 17:36:28 | 1100.0 | -0.1292 | -5.1970 |
| Titan-47 | 19-NOV-2008 15:57:33 | 1022.6 | -0.1114 | -0.7570 |
| Titan-48 | 05-DEC-2008 14:26:50 | 960.0 | 4.6E-03 | -0.6340 |
| Titan-49 | 21-DEC-2008 13:00:57 | 970.0 | 0.0189 | -0.5550 |
| Titan-50 | 07-FEB-2009 08:51:57 | 960.0 | 0.8052 | -6.7640 |
| Titan-51 | 27-MAR-2009 04:44:42 | 960.0 | 0.2846 | -2.6490 |
| Titan-52 | 04-APR-2009 01:48:53 | 4150.0 | -0.4698 | 3.3590 |
| Titan-53 | 20-APR-2009 00:21:51 | 3600.0 | 0.0417 | 1.2500 |
| Titan-54 | 05-MAY-2009 22:55:21 | 3244.4 | -0.1381 | 1.9960 |
| Titan-55 | 21-MAY-2009 21:27:47 | 965.0 | 0.0808 | -0.6820 |
| Titan-56 | 06-JUN-2009 20:01:06 | 965.0 | 0.1131 | -2.6800 |
| Titan-57 | 22-JUN-2009 18:33:41 | 955.0 | 0.0113 | -0.0570 |
| Titan-58 | 08-JUL-2009 17:05:09 | 965.0 | 0.2495 | -0.7820 |
| Titan-59 | 24-JUL-2009 15:35:09 | 955.0 | 0.1368 | -1.2090 |
| Titan-60 | 09-AUG-2009 14:04:59 | 970.0 | 0.1024 | -1.1020 |
| Titan-61 | 25-AUG-2009 12:52:44 | 970.0 | -0.4147 | 9.2960 |
| Titan-62 | 12-OCT-2009 08:37:30 | 1300.0 | 0.1894 | 0.5160 |
| Enceladus-7 | 02-NOV-2009 07:43:04 | 100.0 | -0.1396 | 0.0980 |
| Enceladus-8 | 21-NOV-2009 02:10:56 | 1604.0 | 6.6178 | 6.3880 |
| Titan-63 | 12-DEC-2009 01:04:20 | 4850.0 | -0.2657 | 2.5030 |
| Titan-64 | 28-DEC-2009 00:18:05 | 955.0 | -0.3671 | 3.6770 |
| Titan-65 | 12-JAN-2010 23:11:42 | 1072.8 | -0.0886 | -1.1780 |
| Titan-66 | 28-JAN-2010 22:29:55 | 7490.4 | 0.6891 | 3.9510 |
| Rhea-2 | 02-MAR-2010 17:41:42 | 100.0 | -0.0771 | -0.5630 |
| Titan-67‡ | 05-APR-2010 15:51:44 | 7461.9 | 15.7770 | 24.3790 |
| Dione-2 | 07-APR-2010 05:17:17 | 500.0 | 0.0120 | -6.5350 |
| Enceladus-9 | 28-APR-2010 00:11:23 | 100.0 | 0.0252 | -1.4320 |
| Enceladus-10‡ | 18-MAY-2010 06:05:46 | 438.9 | 0.3283 | -2.6520 |
| Titan-68 | 20-MAY-2010 03:25:26 | 1400.0 | 0.2785 | 2.3610 |
| Titan-69 | 05-JUN-2010 02:27:33 | 2044.1 | -4.4E-03 | 1.6570 |
| Titan-70 | 21-JUN-2010 01:28:49 | 880.0 | -0.0632 | 1.9500 |
| Titan-71 | 07-JUL-2010 00:23:51 | 1005.0 | 0.0607 | 1.3310 |
| Enceladus-11 | 13-AUG-2010 22:32:05 | 2551.6 | -7.2345 | -4.8460 |
| Titan-72 | 24-SEP-2010 18:39:47 | 8174.9 | 0.0741 | -2.7950 |
| End of Equinox Tour, Beginning of Solstice Tour | | | | |
| Titan-73 | 11-NOV-2010 13:38:07 | 7920.7 | 2.3E-03 | -4.9670 |
| Enceladus-12 | 30-NOV-2010 11:55:05 | 50.0 | 0.6036 | 2.2170 |
| Enceladus-13 | 21-DEC-2010 01:09:32 | 50.0 | 0.9470 | -0.4940 |
| Rhea-3 | 11-JAN-2011 04:54:31 | 75.0 | 5.1E-03 | 5.5510 |
| Titan-74 | 18-FEB-2011 16:05:17 | 3650.7 | 0.2339 | -0.3900 |
| Titan-75 | 19-APR-2011 05:01:45 | 10052.8 | -0.0385 | -0.0610 |
| Titan-76 | 08-MAY-2011 22:54:51 | 1873.2 | -0.5064 | 0.4860 |
| Titan-77 | 20-JUN-2011 18:33:07 | 1358.7 | -0.422 | -0.1030 |
| Titan-78 | 12-SEP-2011 02:51:12 | 5821.4 | -0.0526 | 0.010 |
| Enceladus-14 | 01-OCT-2011 13:53:32 | 100.0 | -0.1034 | -0.102 |
| Enceladus-15 | 19-OCT-2011 09:23:18 | 1236.1 | -0.0426 | -0.54 |
| Enceladus-16 | 06-NOV-2011 04:59:59 | 500.0 | 0.1535 | 0.854 |
| Dione-3‡ | 12-DEC-2011 09:40:29 | 99.7 | 0.6373 | 1.957 |
| Titan-79 | 13-DEC-2011 20:12:30 | 3585.8 | -0.8094 | -2.774 |

† The deltas do not necessarily illustrates a navigation error. Targets are sometimes adjusted in flight to benefit from propellant savings. All differences were assessed by science and engineering on approach to each encounter.
‡ Part of double encounter. Reference not specifically targeted.

**Table 3. Navigation Performance Summary**

| Target | Last Control Point † | 3D Position Error (km) | 3D Position Error ($\sigma$) | Delivery Accuracy Probability (%) | Notes |
|---|---|---|---|---|---|
| Titan-45 | OTM-160 | 0.63 | 0.75 | 10 | |
| Enceladus-4 | OTM-163 OD | 1.45 | 1.12 | 26 | |
| Enceladus-5 | OTM-166 | 0.5 | 1.13 | 27 | $> 1\sigma$ pre-encounter RWA bias error |
| Titan-46 | OTM-169 | 9.7 | 4.0 | 99 | 1.8 $\sigma$ pre-encounter RWA bias error and 5.4 $\sigma$ OTM error. Double Encounter with Enceladus-6 |
| Titan-47 | OTM-172 OD | 0.6 | 1.4 | 42 | |
| Titan-48 | OTM-175 | 0.6 | 0.9 | 15 | |
| Titan-49 | OTM-178 | 0.4 | 1.3 | 34 | $1\sigma$ pre-encounter RWA bias error |
| Titan-50 | OTM-181 OD | 0.2 | 1.4 | 40 | |
| Titan-51 | OTM-184 OD | 0.3 | 2.4 | 87 | |
| Titan-52 | OTM-186 | 5.0 | 1.6 | 54 | $1\sigma$ OTM error |
| Titan-53 | OTM-190 OD | 0.28 | 0.8 | 12 | |
| Titan-54 | OTM-193 OD | 0.20 | 0.3 | 1 | |
| Titan-55 | OTM-196 | 0.96 | 1.6 | 56 | $2.4\sigma$ OTM error |
| Titan-56 | OTM-199 OD | 0.46 | 1.2 | 29 | |
| Titan-57 | OTM-202 OD | 0.47 | 0.9 | 16 | |
| Titan-58 | OTM-205 OD | 0.11 | 0.5 | 3 | |
| Titan-59 | OTM-208 OD | 0.50 | 0.8 | 10 | |
| Titan-60 | OTM-211 OD | 0.41 | 0.7 | 7 | |
| Titan-61 | OTM-214 OD | 1.07 | 0.5 | 4 | |
| Titan-62 | OTM-217 | 1.5 | 3.4 | 99 | $4\sigma$ OTM magnitude error, $1.3\sigma$ in RA |
| Enceladus-7 | OTM-220 | 2.8 | 1.7 | 58 | 2.5 km Enceladus downtrack error |
| Enceladus-8 | OTM-222 OD | 6.1 | 1.7 | 61 | Poor knowledge of S/C state from E7 (out-of-plane); control point was 10 days prior |
| Titan-63 | OTM-226 OD | 2.6 | 1.8 | 67 | |
| Titan-64 | OTM-229 OD | 1.5 | 1.3 | 39 | |
| Titan-65 | OTM-232 | 2.4 | 2.0 | 73 | |
| Titan-66 | OTM-235 OD | 1.0 | 0.7 | 7 | |
| Rhea-2 | OTM-238 OD | 3.6 | 2.7 | 94 | 3 km downtrack, 1.5km out-of-plane Rhea ephemeris error |
| Dione-2 | OTM-241 | 7.0 | 3.4 | 99 | 6 km Dione ephemeris error |
| Enceladus-9 | OTM-244 OD | 1.9 | 1.2 | 32 | |
| Titan-68 | OTM-247 OD | 2.1 | 0.8 | 10 | Double Encounter with Enceladus-8 |
| Titan-69 | OTM-250 | 1.7 | 1.0 | 17 | |
| Titan-70 | OTM-253 | 1.9 | 1.6 | 52 | |
| Titan-71 | OTM-256 | 1.9 | 0.8 | 12 | |
| Enceladus-11 | OTM-259 OD | 2.2 | 1.6 | 54 | Control point was 10 days prior |
| Titan-72 | OTM-262 OD | 0.4 | 0.7 | 8 | |
| End of Equinox Tour, Beginning of Solstice Tour | | | | | |
| Titan-73 | OTM-265 | 3.0 | 5.2 | 99 | $4\sigma$ mnvr error in mag |
| Enceladus-12 | OTM-268 | 2.5 | 1.4 | 43 | Preliminary DCO used |
| Enceladus-13 | OTM-271 OD | 0.3 | 0.7 | 8 | |
| Rhea-3 | OTM-274 | 0.7 | 0.4 | 1 | |
| Titan-74 | OTM-277 OD | 2.4 | 1.0 | 20 | |
| Titan-75 | OTM-280 | 0.4 | 2.9 | 96 | $> 1\sigma$ OTM error, 1.5 $\sigma$ Titan error |
| Titan-76 | OTM-283 | 0.8 | 0.9 | 13 | $> 1\sigma$ OTM error |
| Titan-77 | OTM-286 | 0.2 | 1.1 | 25 | $> 1\sigma$ OTM error |
| Titan-78 | OTM-288 OD | 1.57 | 4.65 | 99 | Saturn ephemeris error |
| Enceladus-14 | OTM-292 | 1.6 | 1.9 | 69 | |
| Enceladus-15 | OTM-295 OD | 2.9 | 1.4 | 43 | |
| Enceladus-16 | OTM-298 OD | 0.4 | 1.7 | 57 | |
| Titan-79 | OTM-301 | 10.8 | 4.2 | 99 | Dione ephemeris error from double encounter with Dione-3 |

† OTM stands for Orbit Trim Maneuver. Lines marked with OD denotes a cancelled maneuver, in which case the last control point is from the Final OD delivery. Otherwise corresponds to the OD error plus the OTM execution error model.



(a) Titan-45 (b) Enceladus-4 (c) Enceladus-5 (d) Titan-46

(e) Titan-47 (f) Titan-48 (g) Titan-49 (h) Titan-50

(i) Titan-51 (j) Titan-52 (k) Titan-53 (l) Titan-54

(m) Titan-55 (n) Titan-56 (o) Titan-57 (p) Titan-58

**Figure 1. Navigation Performance for T45 to T58**

Each plot shows the reconstructed encounter-relative positions in the Bplane (blue ODR labels), compared to predictions (red OD.OTM or orange "Target" labels) from Navigation's last control points. The OD solutions are depicted by the mean (where the label starts) and the associated 1-$\sigma$ uncertainty ellipses around them. For most cases, the uncertainty ellipses for the reconstructed OD solutions (blue ODR) are too small for the scale of the plots. The red OD.OTM targets denotes a case where the approach maneuver was cancelled, in which case the last control point correspond to the final OD delivery made at the time of cancellation. The orange "Target" control points correspond to the approach maneuver delivery errors, which are a combination of the OD errors at the time plus the maneuver execution error model.

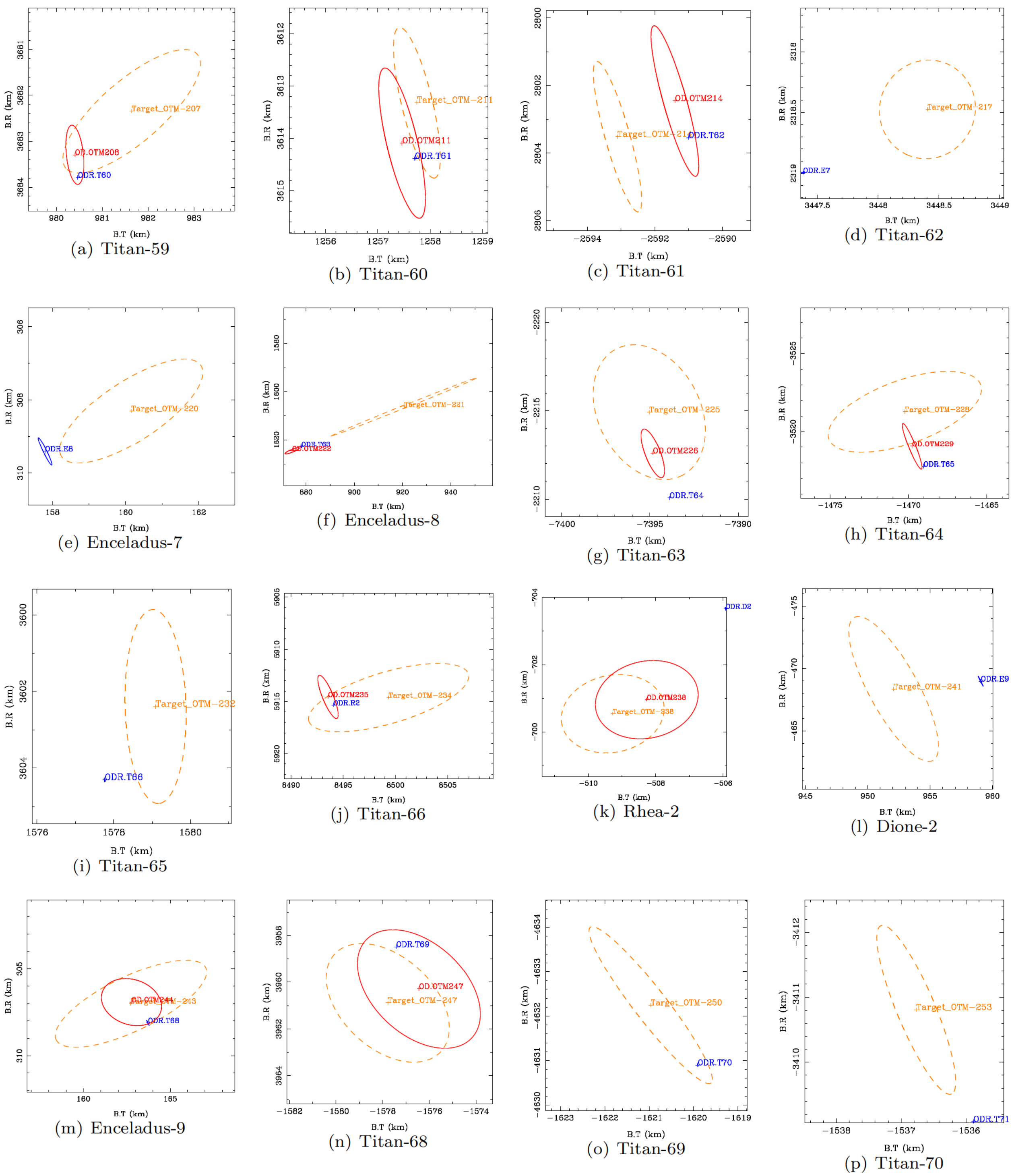



**Figure 2. Navigation Performance for T59 to T70**

Each plot shows the reconstructed encounter-relative positions in the Bplane (blue ODR labels), compared to predictions (red OD.OTM or orange "Target" labels) from Navigation's last control points. The OD solutions are depicted by the mean (where the label starts) and the associated 1-$\sigma$ uncertainty ellipses around them. For most cases, the uncertainty ellipses for the reconstructed OD solutions (blue ODR) are too small for the scale of the plots. The red OD.OTM targets denotes a case where the approach maneuver was cancelled, in which case the last control point correspond to the final OD delivery made at the time of cancellation. The orange "Target" control points correspond to the approach maneuver delivery errors, which are a combination of the OD errors at the time plus the maneuver execution error model.

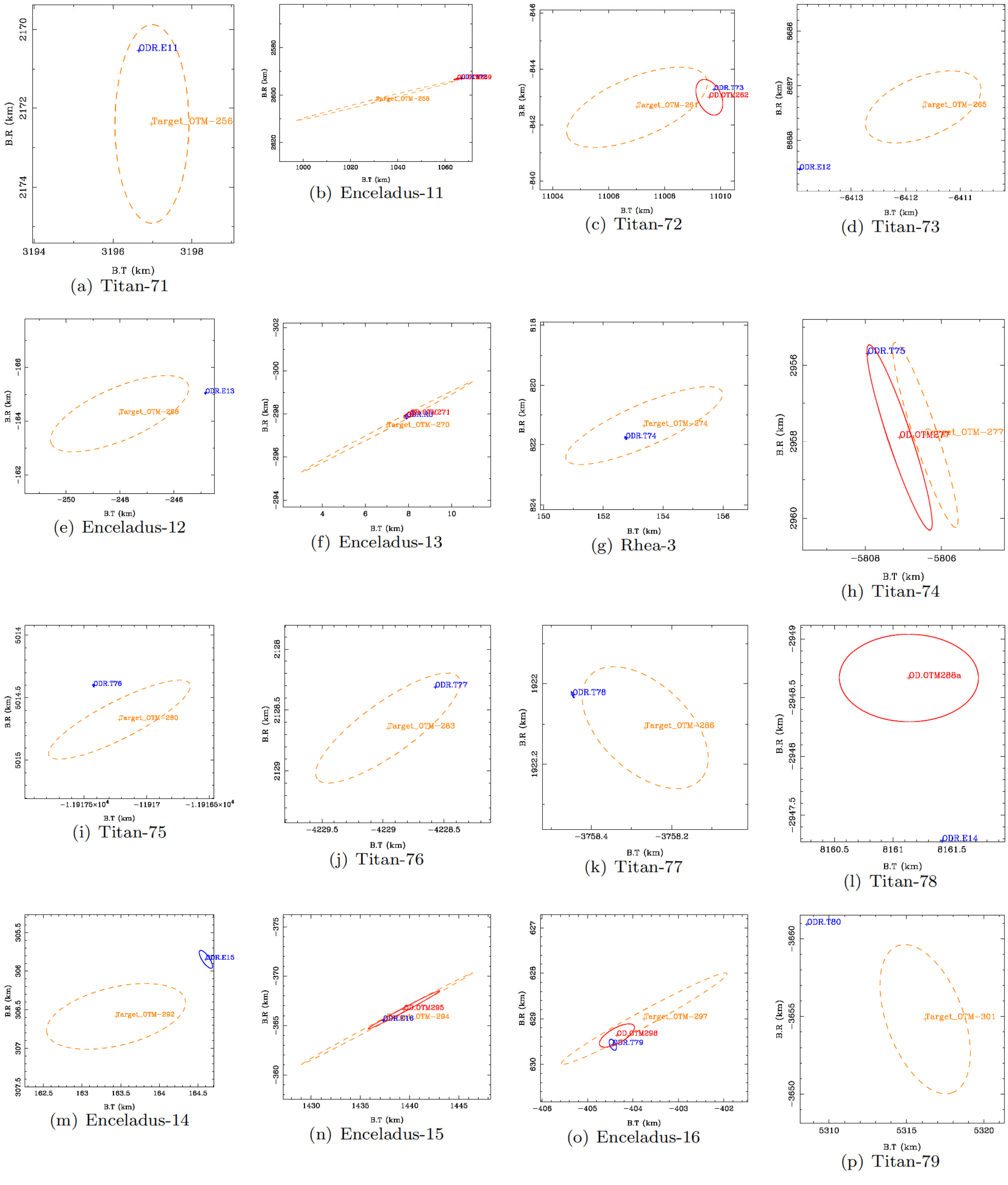
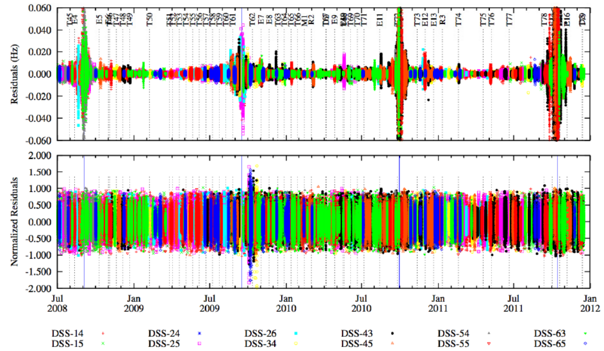
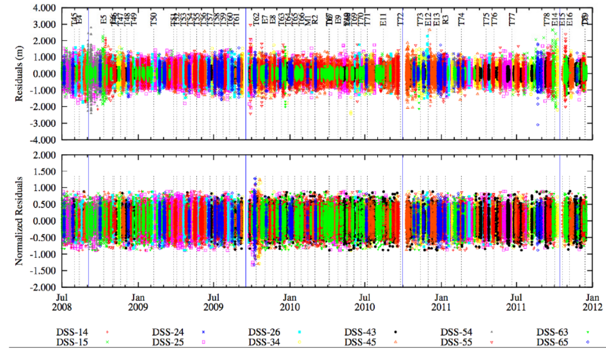


**Figure 3. Navigation Performance for T71 to T79**

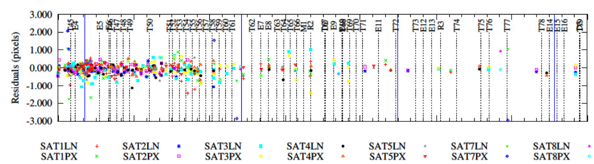
Each plot shows the reconstructed encounter-relative positions in the Bplane (blue ODR labels), compared to predictions (red OD.OTM or orange "Target" labels) from Navigation's last control points. The OD solutions are depicted by the mean (where the label starts) and the associated 1-$\sigma$ uncertainty ellipses around them. For most cases, the uncertainty ellipses for the reconstructed OD solutions (blue ODR) are too small for the scale of the plots. The red OD.OTM targets denotes a case where the approach maneuver was cancelled, in which case the last control point correspond to the final OD delivery made at the time of cancellation. The orange "Target" control points correspond to the approach maneuver delivery errors, which are a combination of the OD errors at the time plus the maneuver execution error model.



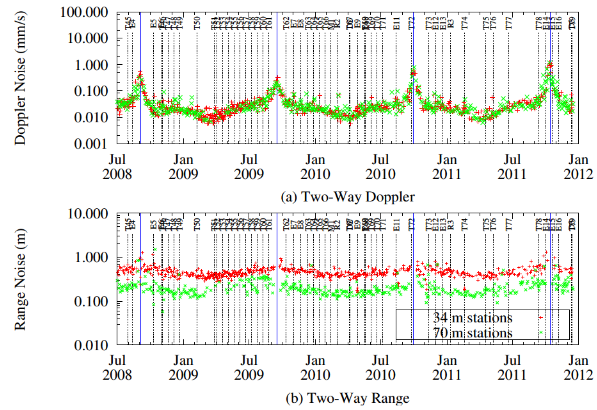

(a) Two-way Doppler




(b) Range



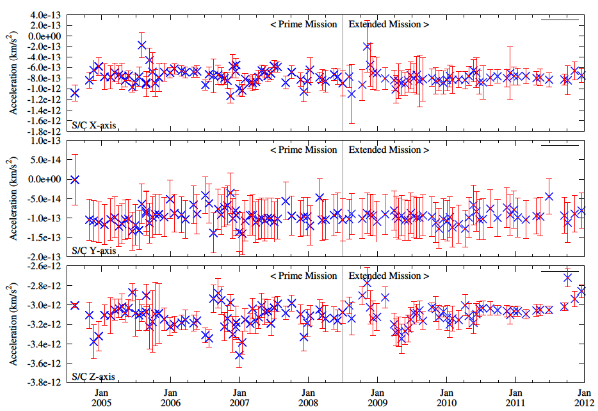

(c) OpNav



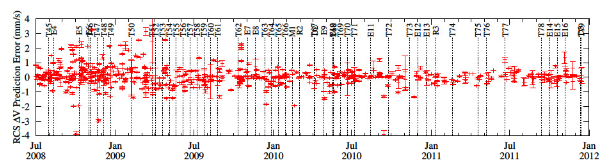

(d) Measurement Noise

**Figure 4. Measurement Residuals**

Color correspond to various DSN tracking stations. The radio metric residuals are shown in Hz as well as normalized by the respective weight, which is applied per pass. On average, a 9-hour tracking pass per day is processed, each corresponding to approximately 6 hours of 2-way Doppler and Range. Opnavs were shuttered every orbits in the prime tour but greatly reduced to approximately 2 per month in the extended mission.



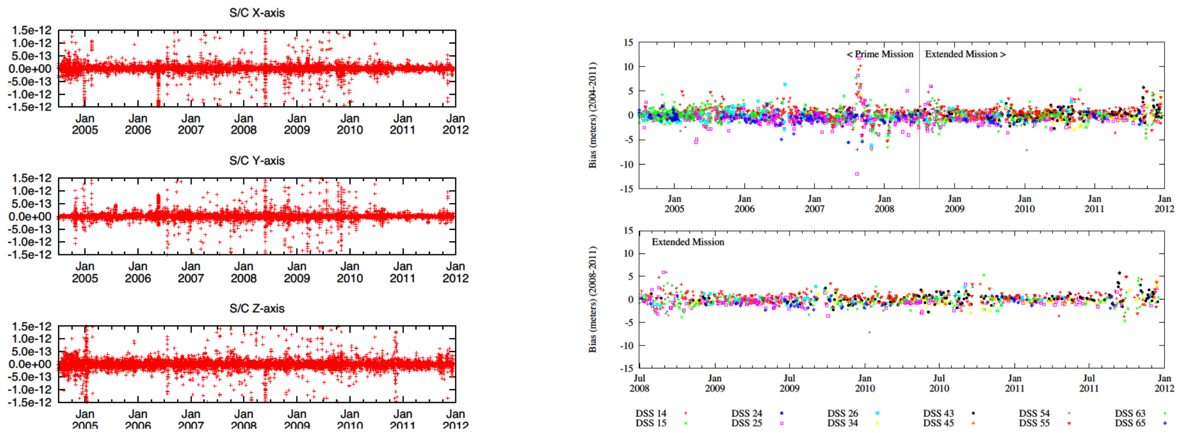

(a) Thermal Radiation Acceleration




(b) Small Forces

**Figure 5. Thermal Radiation Accelerations and Small Forces Estimates History**

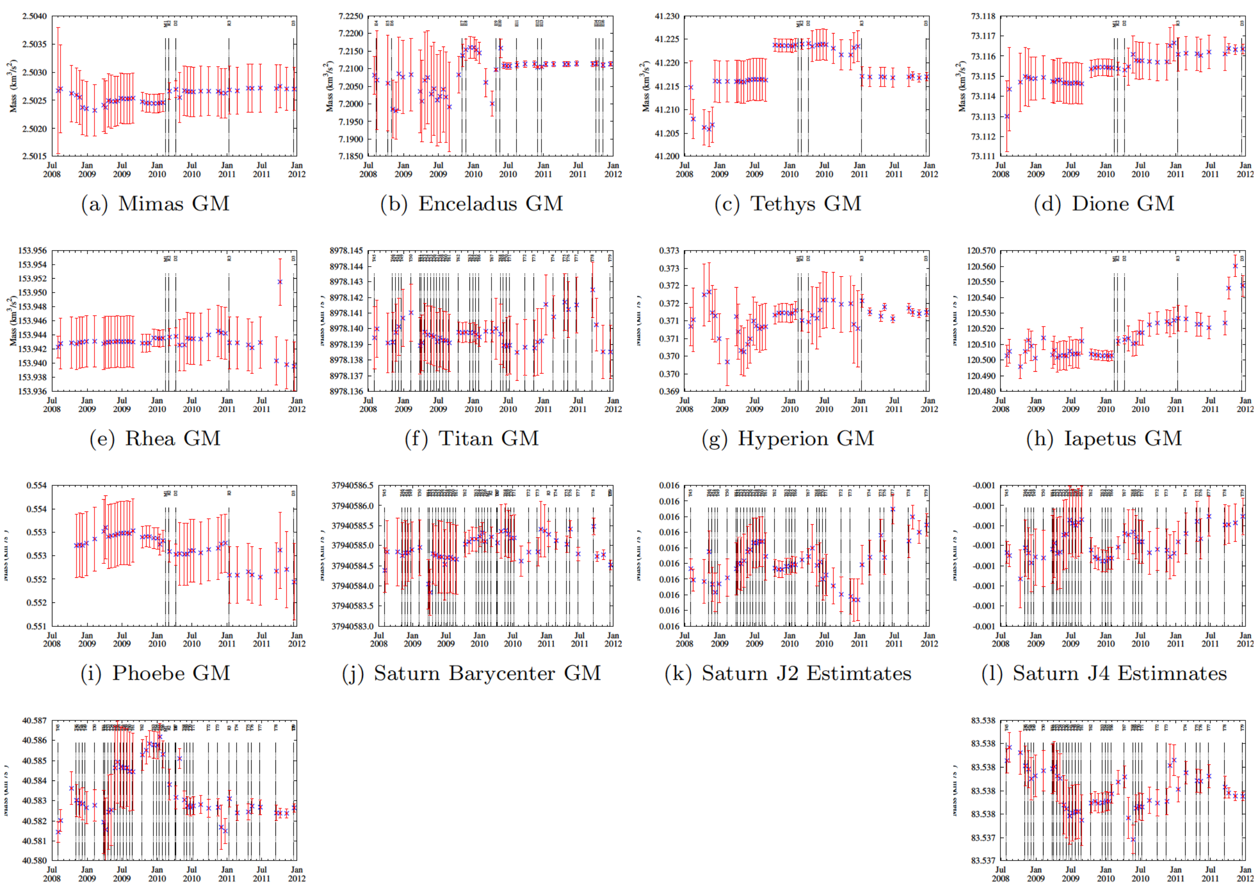
All data shown with post-fit $1\sigma$ uncertainties. Small Forces corresponding to RWA biases are performed 5 times per orbit, on average. More than 600 small forces have been done between July 2008 and December 2011. Thermal radiation accelerations have been normalized to the pre-tour spacecraft mass.




(a) Stochastic Accelerations (b) Range Bias

**Figure 6. Stochastic Parameter Estimates History**

Range biases colors correspond to various tracking passes shown in Figure 4(b). Post-fit stochastic accelerations shown. Apriori uncertainty level is at $5 \times 10^{-13} km/s^2$ most of the time, except for special cases such as low altitude Titan encounters.



(a) Mimas GM (b) Enceladus GM (c) Tethys GM (d) Dione GM

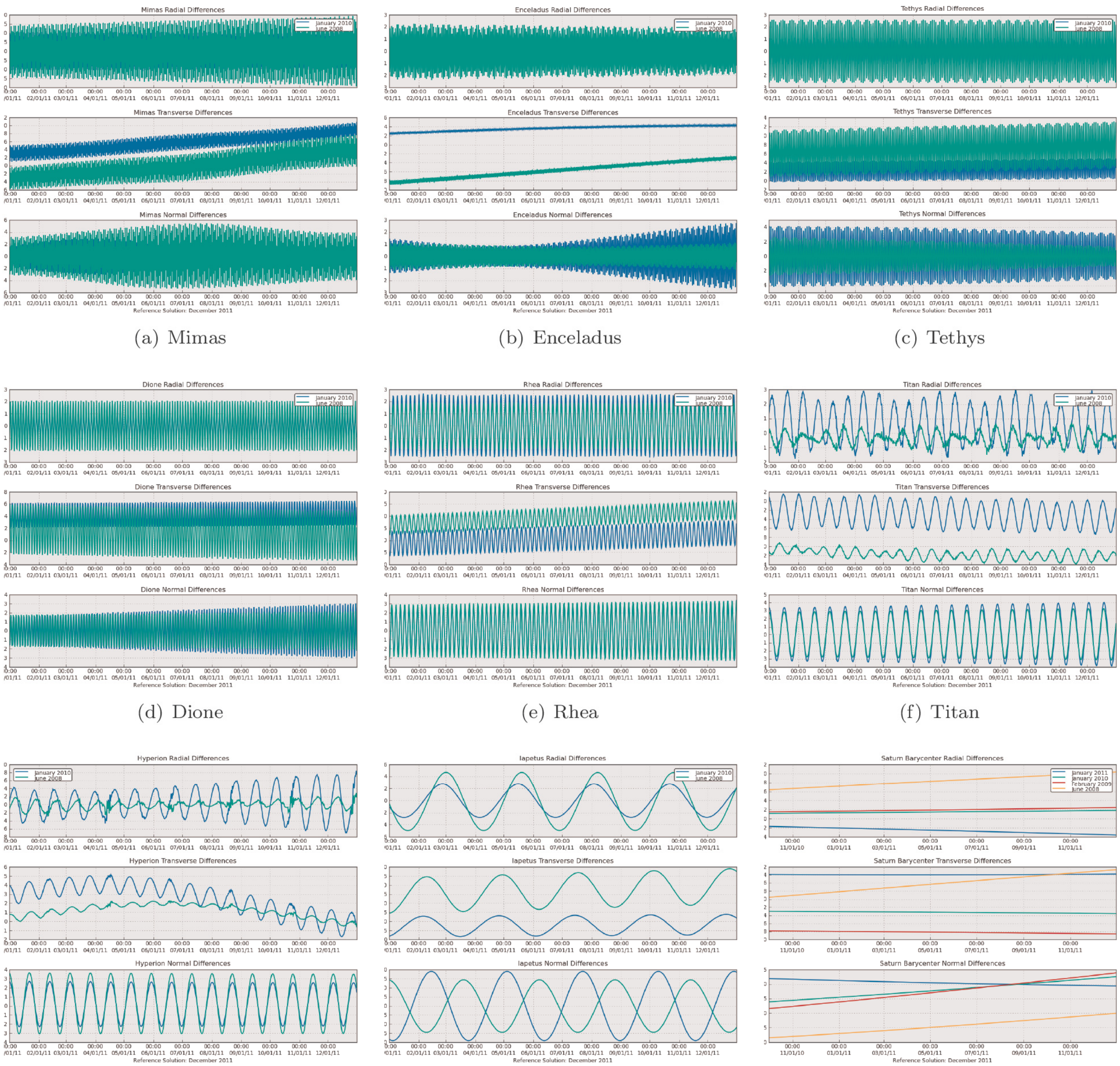
(e) Rhea GM (f) Titan GM (g) Hyperion GM (h) Iapetus GM

(i) Phoebe GM (j) Saturn Barycenter GM (k) Saturn J2 Estimtates (l) Saturn J4 Estimnates

(m) Saturn Pole Right Ascension (n) Saturn Pole Declination

**Figure 7. Saturn and Satellite Parameter Estimates History**

All results shown correspond to estimates for all OD arcs from July 2008 to December 2011 with post-fit $1\sigma$ uncertainties. Relevant encounters are shown with a vertical bar with a label on each plots.



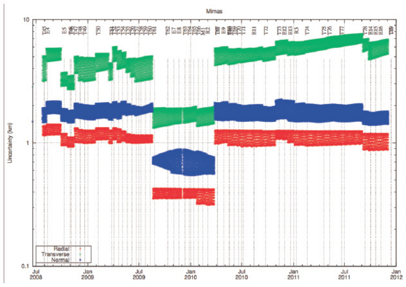

(a) Mimas (b) Enceladus (c) Tethys

(d) Dione (e) Rhea (f) Titan

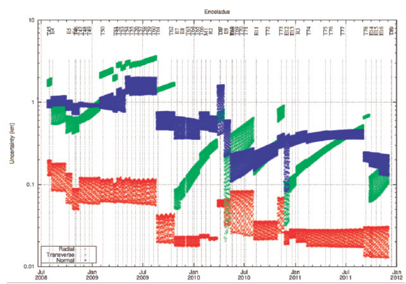
(g) Hyperion (h) Iapetus (i) SaturnBarycenter

**Figure 8. Reconstructed Trajectory Differences**

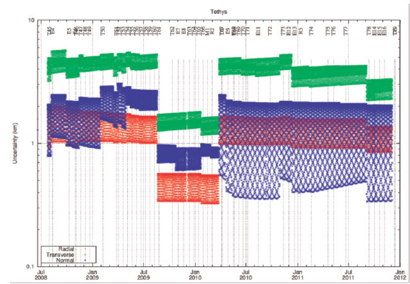
Trajectory differences plotted for one year (January 2011 to December 2011). The reference trajectory used in the plots correspond to the December 2011 reconstructed solution. Plots show how well this segment of ephemerides were predicted by solutions from June 2008 (green) and January 2010 (blue).



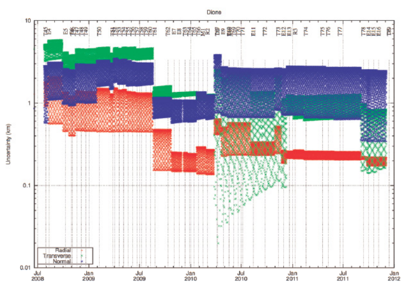

(a) Mimas



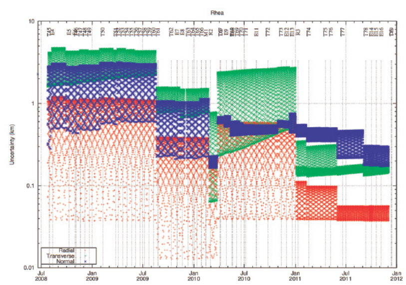

(b) Enceladus



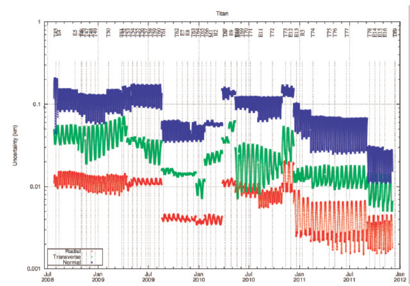

(c) Tethys



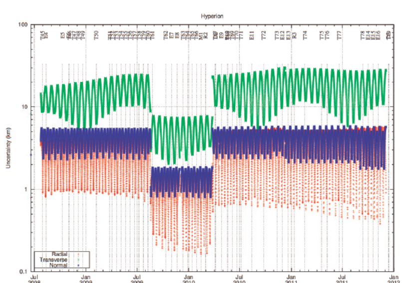

(d) Dione



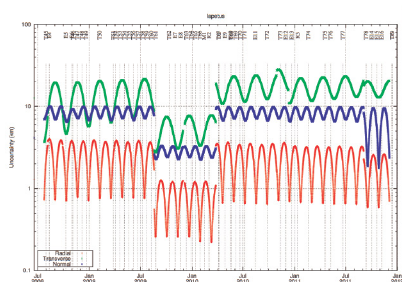

(e) Rhea



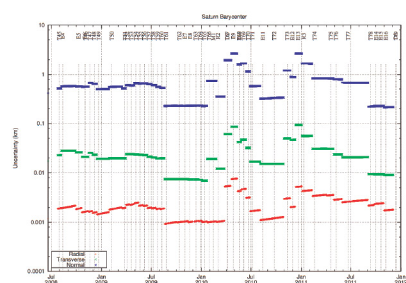

(f) Titan



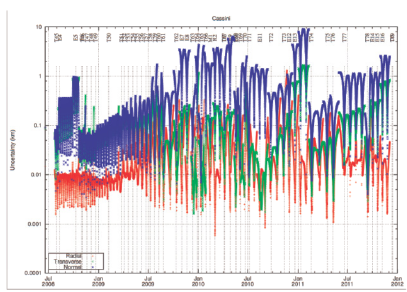

(g) Hyperion




(h) Iapetus




(i) Saturn Barycenter




(j) Cassini

**Figure 9. Reconstructed Trajectory Uncertainties**

Reconstructed ephemeris uncertainties shown in Radial (red), Transverse (green) and Normal (blue) direction for all satellites, barycenter and spacecraft from July 2008 to December 2011.